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Deployment of LTE In-Band Relay and Micro Base Stations in a Realistic Metropolitan Scenario

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Abstract **— Complementing macro-only cellular networks with low-powered base stations is a promising deployment solution to improve both network coverage and capacity, and cope with exploding data traffic in the coming years. In Beyond 3G Networks, such as LTE-Advanced, Relay Nodes and micro base stations can transmit on the same spectrum as the overlaying macro layer, and guarantee higher spatial reuse through cell splitting. Differently from previous research studies, this paper specifically aims at evaluating and comparing the potential of LTE relay and micro deployment in a realistic metropolitan scenario. A heuristic deployment algorithm which combines network coverage and realistic spatial user density information is also proposed. The results show that for the downlink, in-band relays can be deployed to improve network coverage, but not substantially the network capacity due to the limitation of the wireless backhaul link. In-band micro deployment, on the other hand, is the best solution to boost downlink network capacity (up to 5 times), while also providing full network coverage.**

I. INTRODUCTION

The demand for higher mobile broadband data traffic is growing very fast: attractive data plans from operators, attractive smartphones, tablet computers, notebooks with built-in 3G and data dongles are all contributing to this [1]. In order to cope with the demand and simultaneously guarantee sufficient data-rate speeds, mobile operators are expected to upgrade the current network with new features. These upgrades include the roll out of next generation technologies, such as LTE and its next evolution, LTE-Advanced [2]. As the acquisition of more spectrum or deployment of new macro sites generally requires major investments, the deployment of small low-powered base stations is a promising solution that will enhance user experience with reasonable expenditure. Moreover, a significant amount of LTE spectrum will be released at higher frequency bands (e.g. 2.6 GHz), implying higher attenuation and potentially, as a result, coverage issues. Because of this, complementing the existing macro cell site infrastructure with small cells makes it possible to improve network coverage and provide a capacity boost in dense urban areas. One of the biggest obstacles and cost drivers for the deployment of small cells is backhaul. Clearly, fiber access would be preferred but is in most cases far too expensive and not feasible from planning permission perspective. Other alternatives for backhaul are wireless transmission in other bands (e.g. microwave, WiFi or LTE), inband relaying, DSL, powerline communications [3].

In this paper, In-band Relay Nodes (RNs) [2], which will be part of LTE-Advanced, are considered. Besides providing extended LTE coverage, relays guarantee low installation costs and wireless backhauling without the need for new spectrum, which is a scarce resource in many countries. In-band Relaying utilizes the same spectrum and carrier frequencies as used at the macro layer, which has deployment advantages but comes with tradeoff in capacity and shared resource usage. This paper also considers micro base stations which do not require macro spectrum resources for backhauling data towards the core network but have other means of backhauling. The cost and feasibility of micro base station backhaul are outside the scope of this paper.

The performance of relays and micro base stations has already been extensively studied using regular deployment scenarios [4][5]. Realistic network layouts have been addressed in [6][7] for suburban and urban scenarios, considering only relay deployment. The goal of this paper is to investigate and assess the downlink performance gap between relays and micros in a realistic metropolitan deployment scenario. As shown in Fig. 1, the case study considers a section of Vodafone's network [7] located in East London (UK), where the existing 3G macro cell site locations are used as the LTE macro site locations. Furthermore, realistic spatial traffic information and path loss predictions based on ray-tracing are available for this study. The remaining part of the paper is organized as follows: Section II provides the system model description, Section III illustrates the deployment method, Section IV describes the simulation setup, Section V shows the results of the performance analysis, and finally Section VI provides the conclusion.

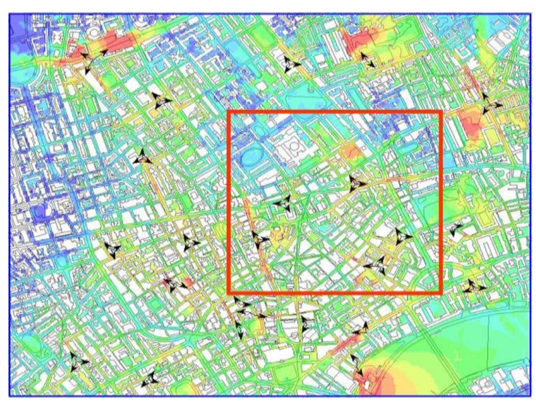

Figure 1: London Area Scenario with existing 3G site deployment. The investigated area delimited by the rectangle.

II. SYSTEM MODEL DESCRIPTION

In the proposed relay system model, Decode-and-Forward (DF) relays are considered within a simple two-hop relay system, where the User Equipment (UE) connects to either the macro cell (eNodeB) or the relay. In such network architecture the terms direct link, backhaul link and access link refer to the eNodeB-to-UE, eNodeB (or Donor)-to-Relay and Relay-to-UE link, respectively. When Micros are considered, the access link is the only one to be considered at the Micro cell side.

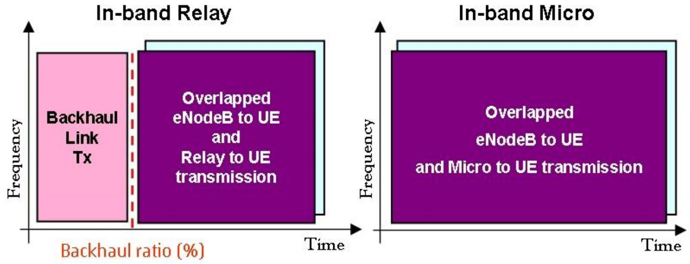

Figure 2: : Resource allocation for In-Band Relays and In-Band Micros.

In this paper, downlink in-band relay deployment is considered, which means that the same carrier is utilized for backhaul, access and direct transmissions. As shown in Fig. 2, relays operate in a half-duplex fashion: within each macro cell, backhaul and access transmissions are split into two different time frames, and the percentage of time frames dedicated to backhaul is indicated with the term Backhaul Ratio. In this study, the backhaul link ratio is optimized on a cell basis in order to improve network coverage or, in other words, minimize the percentage of users that are not satisfied with their QoS. Regarding the downlink transmission towards UEs, direct and relay access transmissions overlap in both frequency and time domain, and interference amongst the different links is modeled. In case multiple relays are connected to the same macro donor eNB, the backhaul link resources are shared among relay nodes, and each of them is assigned a resource share that is proportional to the number of users served in its access link. For the in-band micro spectrum allocation, a plain frequency reuse 1 with the overlaying macro cells is used. In this case macro resources are not consumed to feed relays, and the micros are allowed to transmit continuously over the full bandwidth. In addition, no backhaul constraints are applied for either Macro or Micro cells.

With reference to the direct and access link, each type of base station has to distribute the available resources amongst the connected users. The amount of resources allocated to each user depends on the user Signal-to-Interference-plus-Noise-Ratio (SINR). The SINR of the *n-th* user served by the *l-th* cell with received power level P_l, is defined as follows:

$$SINR_n = \frac{P_l}{N + \sum_{c \neq l} \alpha_c \cdot I_c} \qquad (1)$$

where N is the noise power and I_c, is the interference power received from the *c-th* interferer. Each received interference power is linearly scaled by the fractional load factor α_c, which denotes the ratio between the utilized time-frequency resources to the overall available resources. This evidently affects the interference power generated by relays as the access link transmission is silenced during the backhaul link time frames.

Each cell performs a resource allocation algorithm which is composed of the following two phases: in the first phase, the available resources are allocated in such a way that each user is ensured a predefined minimum required data rate. The resources are first allocated to the users with high SINR as they require the least amount of resources to get the required data rate. If additional resources are available, these are distributed to each user in a Round Robin fashion. In case the network load is very high or user SINR is extremely bad, resources may not be sufficient to meet the minimum data-rate for each connected user and the worst-SINR users are likely to be in outage, i.e. their data rate is below the required one. The percentage of users whose experienced data-rate is below a predefined minimum requirement is defined as *user outage* [8].

III. OUTDOOR SMALL CELL DEPLOYMENT STRATEGY

The proposed deployment strategy is aimed at deploying small cells in the outdoor locations of the network area so as to decrease user outage. Based on [6], such a coverage-oriented deployment approach is achieved by designing a specific metric for each potential relay or micro location. The steps of the deployment algorithm are illustrated in Fig. 3.

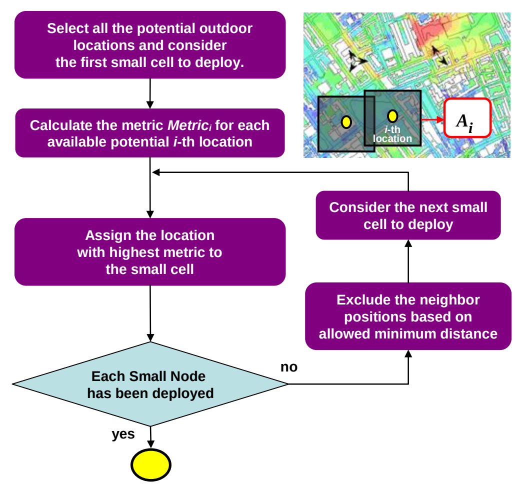

Figure 3: : Iterative Steps for the proposed small cell deployment algorithm

First of all, the set of the candidate locations is given by all the possible outdoor locations within the investigated area, and the spatial resolution is denoted as *pixel*. For each small cell to deploy, the candidate locations are associated with a deployment metric which is calculated over the pixels of a squared area, A_i, surrounding each location. The metric depends on the following macro network measures: normalized per-pixel user density information (*UsDens*), macro Layer coverage and, differently from [6], backhaul link quality referred to the specific candidate location. The metric is formulated as follows:

$$Metric_i = \sum_{pixel_l \in A_i} \frac{UsDens_l \cdot e^{wOut \cdot Outage}}{TP(SINR_l)^{wCov}} \cdot TP^{BH}(SINR_i^{BH})^{wBH} \qquad (2)$$

where the TP and TP^{BH} stand for the wideband throughput related to direct and backhaul link respectively; the throughput terms depend on the SINR values calculated in those specific locations. In order to achieve different deployment strategies, three exponential weights have been introduced in (2): *wCov* biases the weight of macro coverage which depends on the experienced SINR, *wOut* gives stress to the number of users in outage belonging to the macro cell covering the l-th pixel ($Outage_l$), and finally *wBH* weighs the impact of the backhaul link quality for the i-th candidate location. Such weights have been optimized heuristically to achieve the best performances for both relay and micro deployment, as explained in Section V. In order to improve network coverage, the metric formula (2) has to be set with more emphasis on coverage and outage measures, although high backhaul link quality has to be guaranteed to ensure good performances out of relay deployment.

The algorithm operates in an iterative fashion, assigning sequentially the best location to each small cell based on the highest metric. The potential locations in proximity of the assigned ones are removed from the set of candidate locations if those are below a pre-defined minimum distance between neighbor small cells or macro sites. The minimum Inter-Site Distance (ISD) between small cells or between an existing macro and a new small node has been set on the basis of relay/micro transmission power and expected cell size. This enables the algorithm to effectively spread the small cells in the targeted areas and keep at bay the interference level generated by the other small cells.

IV. SIMULATION SETUP

The performance study has been carried out in a metropolitan network scenario which corresponds to an existing Vodafone 3G macro cellular deployment in London, UK. The investigated area, shown in Fig. 1, is 1.1 km x 1 km, and it contains 5 Macro sites each equipped with 3 sectors. The size of a pixel is 10 m x 10 m. The ISD between 2 neighbor macro sites is on average 271 m, just as in typical dense urban macro deployments [7]. For this study, each macro site is considered upgraded to LTE with optimized antenna downtilt angles. In order to avoid border-effects, interfering cells from base stations located outside the examined area are taken into account. To accurately estimate link budgets, a 3D ray-tracing tool [7] is used to evaluate path loss and antenna pattern effects on both Macro and Backhaul link budgets. Such a tool models the radio propagation at street level by considering realistic positions and heights of the buildings. LTE users are generated in the investigated area according to traffic information obtained from the existing 3G network: cell-level data traffic volumes in the busy hour have been utilized together with estimated macro coverage to generate a user density map, whose spatial resolution is equal to one pixel.

The relay and micro system models, deployment algorithm, and network layout previously described have been implemented in a Matlab-based network planning tool including a static network simulator [6][8][9]. A downlink LTE FDD system is considered as an example, with a frequency carrier of 2.6 GHz and a 20 MHz transmission bandwidth. The main simulation parameters are listed in Table I. The performance indicators are obtained by means of a SINR-to-throughput mapping curve [6] for LTE 2x2 MIMO transmission, which is based on extensive link-level simulations. The same transmission scheme is assumed for direct, access and backhaul link. The number of LTE active users is 300 with a minimum target data rate of 1024 kbps; this minimum target data rate is also used to calculate user outage. With the above assumptions, the investigated LTE macro-eNodeB network is able to provide an outage value of only 14.6 % (or equivalent to 85.4 % coverage). Therefore, the number of in-band small cells to be deployed has been varied in order to reduce user outage with a target outage level of 5 %.

TABLE I. MAIN SIMULATION SETUP PARAMETERS

Cellular Layout	Realistic London Area scenario
LTE system	Downlink FDD LTE over a 20 MHz bandwidth at 2.6 GHz
Path Loss model	Based on ray-tracing tool for Direct and Backhaul link. 3GPP model [7] for Relay/Micro access link. Indoor Penetration Loss equal to 20 dB
Traffic Model	Full Buffer, with 1024 kbps as required data rate.
Macro Tx Power	46 dBm
Macro Antenna Pattern	3D antenna pattern from [7] with realistic tilting angles obtained from network data
Relay/Micro Tx Power	30 dBm, with small cells deployed outdoor
Relay/Micro Antenna Pattern	Directional antenna for Backhaul link (12 dBi Gain with 55 ° half-beam width) and 3GPP Omni-antenna [7] for access link.
User settings	300 users placed with Realistic user density map
Deployment algorithm parameters	Side length of $\boldsymbol{A_i}$: 40 m *wCov, wOutage, wBH* : varied Min. New cell ISD: 100 m (Relay), 80 m (Micro) Min. Macro ISD: 150 m (Relay), 100 m (Micro)

Based on the average ISD of existing macro network, the side length of the area A_i has been set to 40 meters in order to sufficiently integrate traffic and coverage information in proximity of the candidate location. The total number of potential outdoor candidate locations is around 6000.

V. RESULTS AND DISCUSSION

In this section, the performances of in-band relays, in-band micros and existing eNodeB-only deployments are analyzed and compared. The results will be shown first for the relay deployment case and then for micro deployment. User SINR, user outage (coverage) and user average throughput are the key performance indicators (KPIs) used to investigate the different network configurations.

Fig. 4 illustrates the cumulative distributions of wideband user SINR for both macro-only and in-band relay deployment at 2.6 GHz. The average user SINR improves by 2.4 dB as compared to the initial macro-only deployment, and this is mainly due to the fact that Relay users experience higher SINR values than the eNodeB users. By setting the deployment algorithm parameter *wCov* to 0.5 [5], RNs tend to be deployed in areas of the network where high interference or low received signal strength (“coverage hole”) limit the downlink performance. In the investigated scenario poor coverage at 2.6 GHz is mainly experienced in cell-edge indoor locations and relay deployment improves coverage especially in those locations. The same conclusion can be drawn when micro base stations are deployed in the same positions of relays as the same path loss model has been utilized for both relay and micro access link. The quality of the backhaul link is significantly better than the one experienced by the direct and relay users as the use of a directional antenna with a 12 dBi gain and accurate relay positioning limit the impact of interference at the relay side.

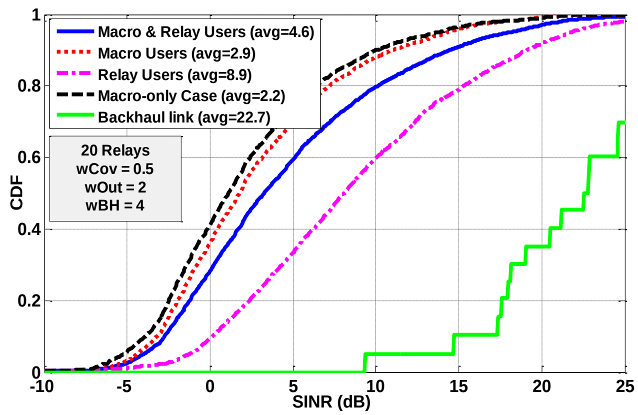

Figure 4: Wideband SINR distributions for eNodeB-only Scenario and In-Band Relay deployment (Direct, Relay and Overall user geometry); see the text for values of the deployment parameters *wCov*, *wOut* and *wBH*.

The SINR distribution curves in Fig. 4 have been obtained by setting *wOut* = 2 and *wBH* = 4, and this solution guarantees the best user outage performance when 20 RNs are deployed in the network. The reason is that a higher weight on the backhaul link measure allows the deployment algorithm to place the relay in those locations of the network where high backhaul link SINR is experienced. A better backhaul link gives the opportunity to fully exploit the potential of in-band relays because the in-band backhaul connection generally acts as a bottle-neck for the relay users' performance. TABLE II shows the sensitivity of user outage and average backhaul link SINR for different settings of the deployment algorithm. If more emphasis is put on *wOut*, relays are deployed in those areas where the serving macro cell has a higher number of users in outage. Yet, such a solution does not give the best outage performance for the simple reason that the low average backhaul link SINR significantly limits the access link performances, and more resources are consumed at the donor eNodeB to serve the backhaul link. With *wOut* and *wBH* equal to 3 and 1 respectively, the poor backhaul signal quality results in an outage level of 19.3 %, which is even worse than the one experienced in the macro-only scenario (14.6 %).

TABLE II. PERFORMANCE SENSITIVITY TO DIFFERENT DEPLOYMENT ALGORITHM SETTINGS FOR 20 RELAYS DEPLOYED IN THE NETWORK

wOut	wBH	Average Backhaul SINR	User Outage
3	1	9.6 dB	19.3 %
3	3	20.8 dB	10 %
2	3	21.9 dB	8.4 %
2	**4**	**22.7 dB**	**8.2 %**

In Fig. 5, user outage performance and average user throughput (or capacity) gain over the macro-only scenario are presented with reference to different numbers of deployed relays. The best deployment algorithm setting previously described has been used for relay deployment. The overall user outage is shown by considering the split between users connected to the relays and those connected to the macro cells. The outage level decreases with increasing number of relays before leveling out at around 8 % between 20 and 30 relays, well above the 5 % target. It can be observed that with 30 RNs the majority of the users in outage belong to the macro layer, but when more than 30 RNs are deployed, the overall user outage is basically caused by relays and it increases steeply. By introducing more relays in the network, more users connect to RNs, but it is also true that the macro donor cell resources have to be shared amongst a higher number of connected relays. As a consequence, the amount of backhaul resources allocated to each single relay is lower and the relay transmission is strongly backhaul-limited. With regard to average throughput, relays yield capacity gains as compared to the eNodeB-only scenario. The throughput gains increase until 30 relays are deployed in the network, before saturating at around 50 %. Relay deployment improves the overall user SINR, and despite the resource consumption on the backhaul link, relay and macro users experience better average throughput than in the macro-only case.

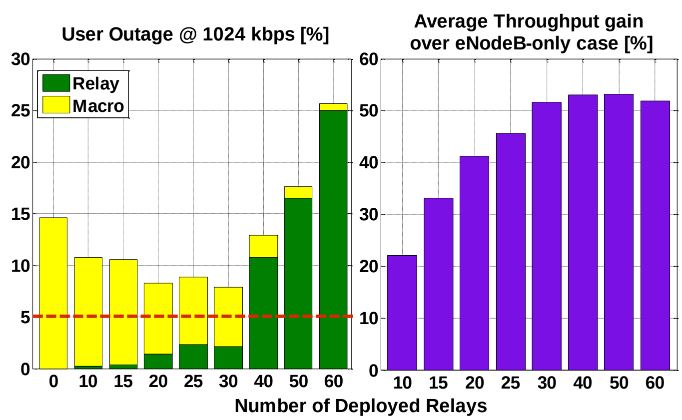

Figure 5: User outage performance and Average user throughput gains over eNodeB-only scenario for different numbers of Relays.

Fig 6 gives further insight into how relays are distributed amongst the different donor eNodeBs. Given a predefined set of potential donors (14 Macro cells), the graph shows the number of donors serving the number of relays specified on the x-axis. With 10 RNs deployed in the network, half the small cells are connected to one donor cell having the worst outage and coverage performances whereas most of the potential donors are not utilized for backhauling (0 relays connected). As the number of relays is increased to 30, they start being spread more uniformly all over the network but a pair of donor cells is the most critical with a maximum of 8 RNs to be fed. In this specific metropolitan scenario, outage users are mainly located in high traffic areas within certain macro cells, and therefore the high traffic load, rather than lack of coverage, determines the overall user outage. In those cells the experienced backhaul link capacity is not sufficient to significantly boost relay users' performance even though good backhaul SINR can be guaranteed. When the network is loaded with 60 relays, the macro cells with the lowest performances are loaded with even more Relays, and the overall user outage level substantially increases due to the in-band backhaul limitation.

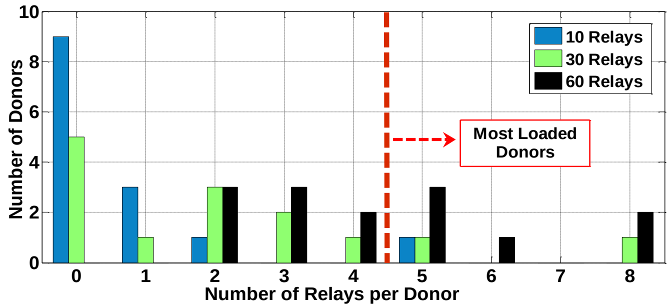

Figure 6: Number of Donor cells over Number of connected Relays per Donor for different number of relays (10,30,60) deployed in the network.

In Fig.7, the same network performances illustrated in Fig. 5 are shown for micro deployment. As micros do not inherently operate with in-band wireless backhaul, the deployment algorithm has been slightly modified: wBH is set at 0 (backhaul link measure deactivated), wOut at 3 and wCov at 0.3 so as to focus the micro deployment in the high traffic areas. It can be observed that micro base stations exhibit lower user outage values as compared to relay deployment, and user outage goes down when increasing the number of micros. Outage users are only connected to eNodeBs because, differently from the relay case, the access link throughput is not limited by the backhaul connection. Moreover, the deployment of micros is also more flexible as there is no need for ensuring extremely good wireless backhaul connection. As a result, a denser small cell deployment can be achieved in highly loaded macro cell areas serving most of the outage users.

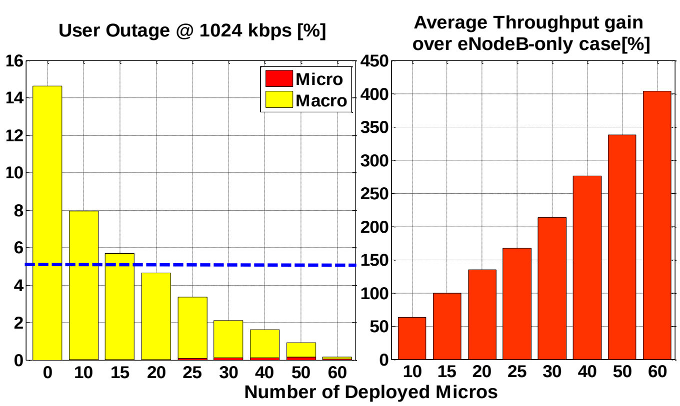

Figure 7: User outage performance and Average user throughput gains over eNodeB-only scenario for different numbers of Micros.

In principle, 20 micros are sufficient to bring down the outage level to the 5%-target and this goal cannot be achieved with a pure relay deployment. Similarly to outage performance, the capacity gains are one order of magnitude higher than those achieved with relays. As the users experience good signal quality on the access link, higher spatial reuse allows for significantly enhancing the micro users' throughput and effectively offloading the overlaying macro layer. The capacity gains increase linearly with the number of deployed micros until reaching a gain of 400 % (5 times) over the macro-only scenario, with 60 micro base stations (4 Micros/cell on average). Moreover, only 10 micros are needed to equal the maximum capacity gain (~50 %) obtained when deploying 30 RNs. Whilst relays have advantages in deployment cost and flexibility, micro deployment is advantageous to boost coverage and capacity in this specific scenario at 2.6 GHz. Relays are more helpful to improve coverage issues but their capacity benefits saturates from a certain relay density onwards.

VI. CONCLUSIONS AND OUTLOOK

This study investigates and compares the performances of downlink Relay vs. Micro deployment for a realistic metropolitan area (London, UK) assuming a minimum user data rate of 1024 kbit/s. With the assumed macro site deployment, 14.6 % of the users are in outage. The results indicate that the use of in-band relays cannot substantially reduce the user outage values (8 % with 20 Relays). Although good backhaul link quality can be achieved through accurate positioning of relays, deploying a larger number of relays does not have a beneficial effect on the user outage. Also, the capacity gain saturates at around 50% compared to the macro-only case. It is noted that outage users are mainly due to high traffic load within a certain few macro cells rather than lack of coverage.

In order to significantly improve the network performance micro base stations could be deployed in the network. It has been shown that under the assumption of no backhaul constraints, micros can significantly reduce user outage and guarantee substantial capacity gains of up to 5 times, even if micro base stations share the frequency band with the Macro network. In order to minimize deployment costs, relaying could be used for coverage-limited locations whereas traffic hotspots should be targeted with micro cells. The deployment cost of small cells, which is mainly driven by backhaul, will determine where in-band relaying or alternative backhaul will be appropriate.

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